# A High-Finesse Fabry-Pérot Cavity for Hall A Compton Polarimetry

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# Introduction

- Principle of Compton polarimetry
- Compton polarimeter at Jefferson Lab
- Hall A Compton polarimeter upgrade

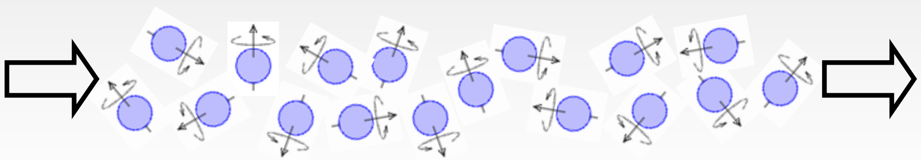
# Implementation of Fabry-Pérot cavity

- Cavity optics
- Cavity resonance modes
- Cavity locking

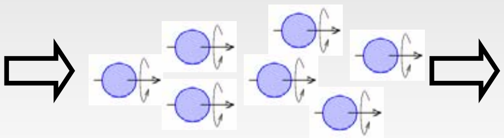
# Summary

# Polarized Electron Source

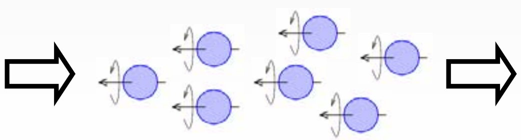
- In a **polarized beam**, the spins point in a single direction. The accelerator at Jefferson Lab can produce two types of longitudinally polarized beam



Unpolarized electrons



Right-handed



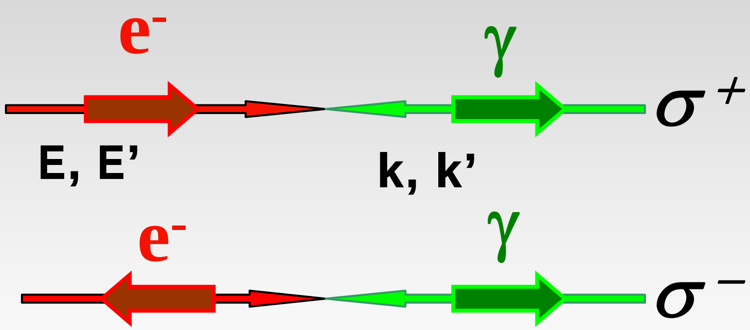
Left-handed

- Via polarized electron scattering, physicists gain insight into what physical processes are involved in an event. This technique is useful for many open research questions, such as:

> **How densely are neutrons distributed in a heavy nucleus like lead ?**
> **Do strange quarks contribute to the physical properties of protons ?**
> **How is electrical charge distributed inside the neutron ?**

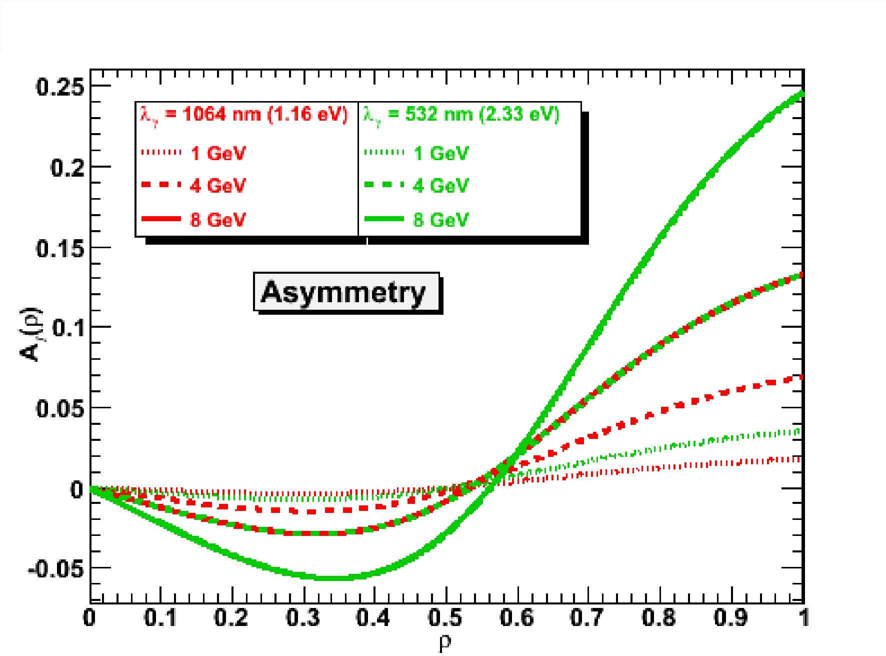
- **Polarimetry**, the measurement of the beam polarization, allows us to accurately interpret the data and control for errors.

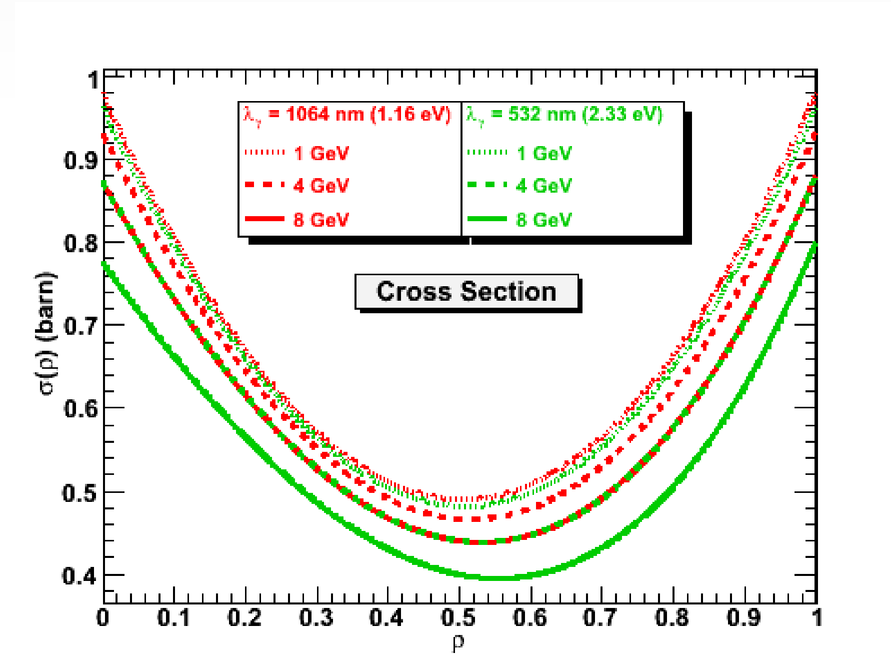
# Principle of Compton Polarimetry




$$\boxed{A_{exp}} = \frac{n^+ - n^-}{n^+ + n^-} = \boxed{P_\gamma} \times \boxed{P_e} \times \boxed{< A_{th} >}$$

**Measurable** **Theoretical Calculation**




$$\frac{\Delta P_e^{stat}}{P_e} \propto \frac{1}{A_l \sqrt{L \sigma \Delta t}} \qquad \frac{\Delta P_e^{syst}}{P_e} \propto \frac{1}{A_l}$$

# Why optical cavity is chosen

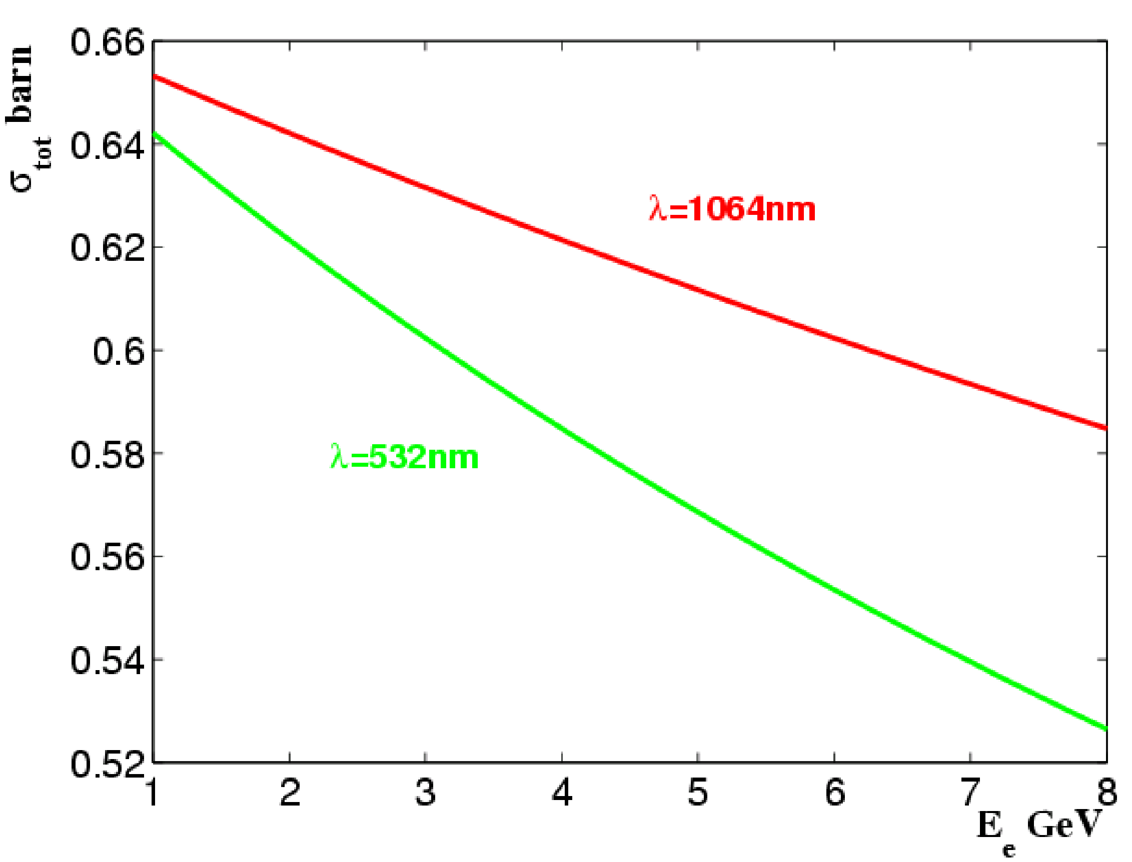
$$\sigma_{tot} \approx \frac{8\pi}{3} r_e^2 (1-x)$$

$$x = \frac{2\gamma\hbar\omega(1+\beta)}{mc^2}$$ <<1

$$r_e = 2.817940325(28) \times 10^{-15}\mathrm{m}$$

$$n = L \times T \times \sigma$$

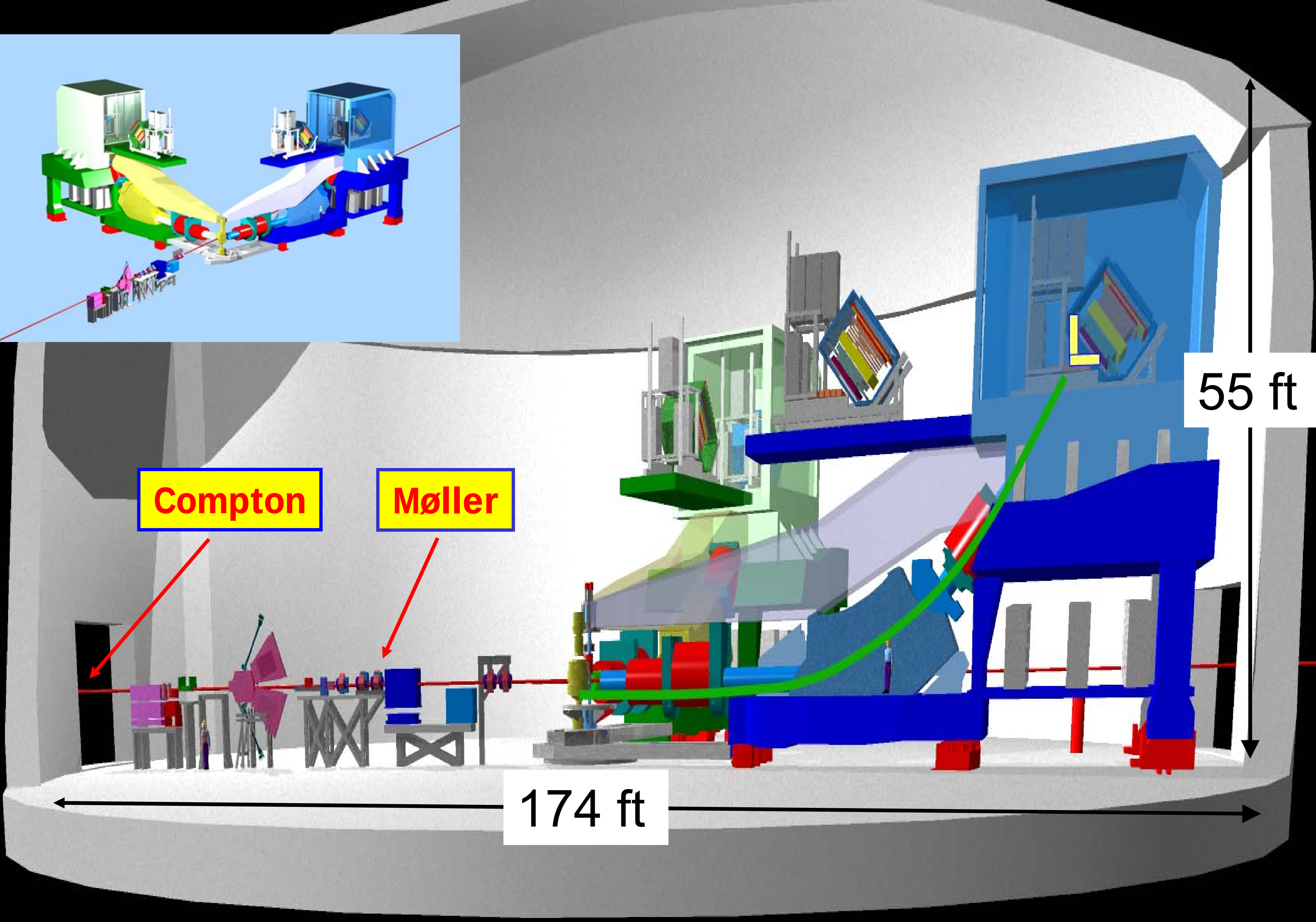
$$L = \iiint v_{rel}\rho_e \boxed{\rho_\gamma} dzdxdy$$



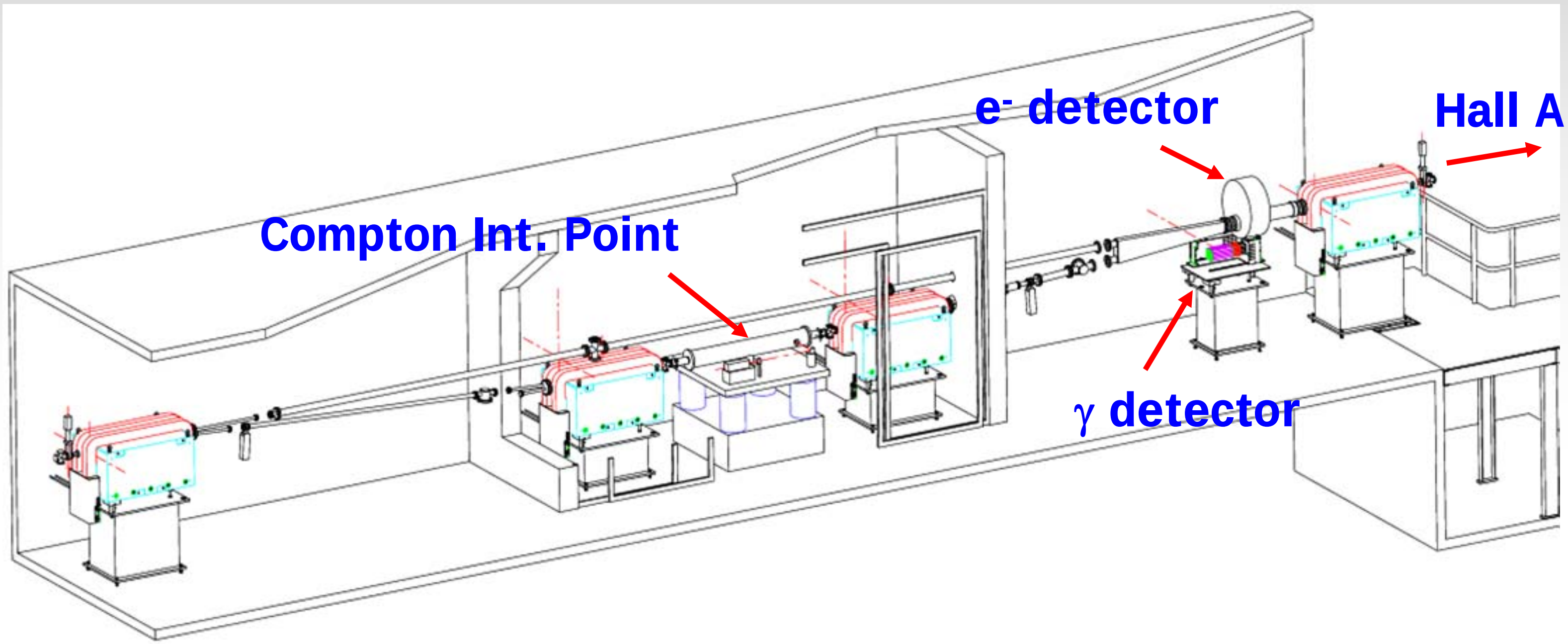

**Amplified by optical cavity:**

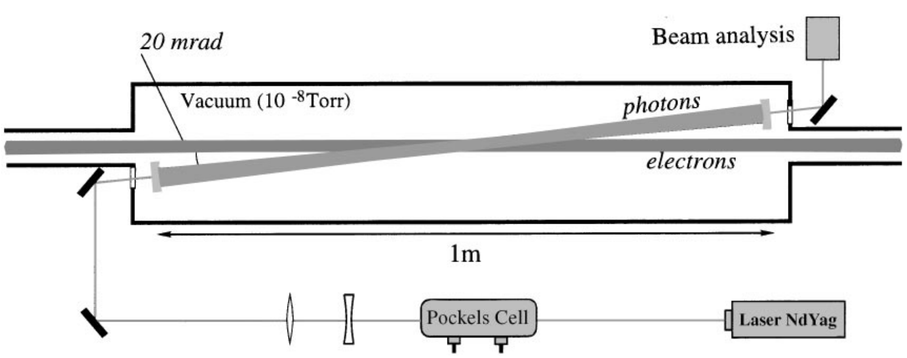
$$L = \mathbf{G} \frac{I_e}{e} \frac{P_L \lambda}{hc^2} \sqrt{\frac{2}{\pi}} \frac{1}{\sqrt{\sigma_e^{y2} + \sigma_\gamma^{y2}}} \frac{1}{sin\alpha}$$

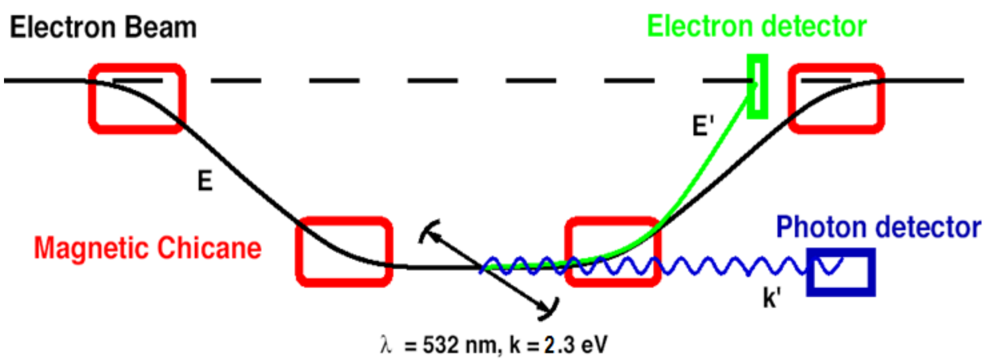
# Compton Polarimeter at Jefferson Lab



# Compton Polarimeter at Jefferson Lab



# Hall A Compton Polarimeter Upgrade

**Motivation:**

Improve accuracy of polarization experiments by providing 1% beam polarimetry down to 1 GeV. High precision parity violating experiments (such as PREx) are feasible with this upgrade.

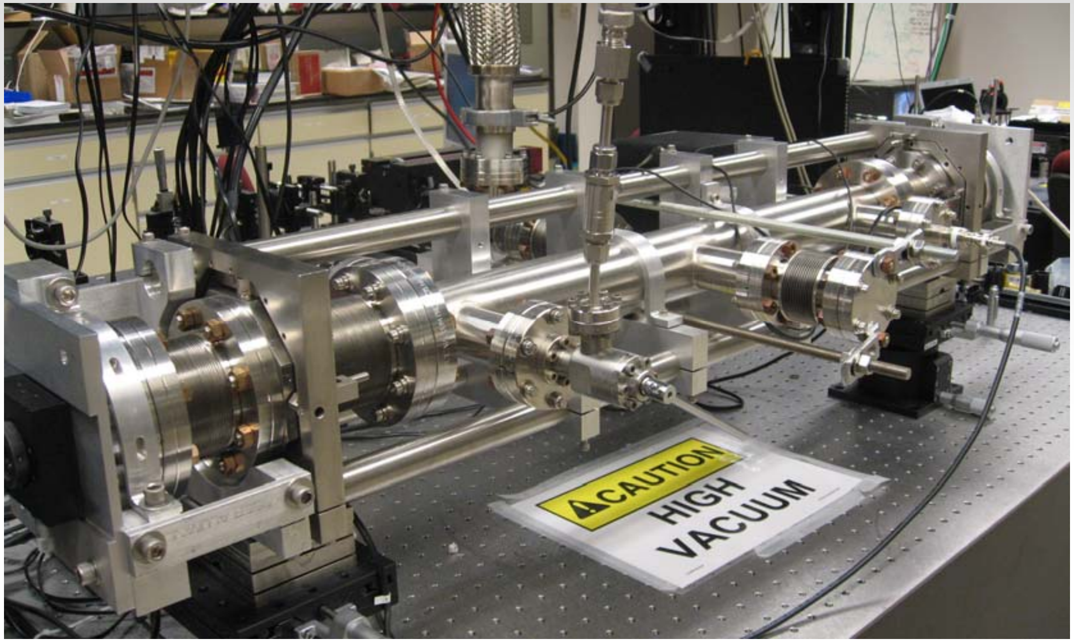
**New Electron Detector :** High resolution silicon micro strips to improve tracking resolution

**New Photon Detector :** Improve systematic uncertainties experienced in the counting method While preserving counting abilities

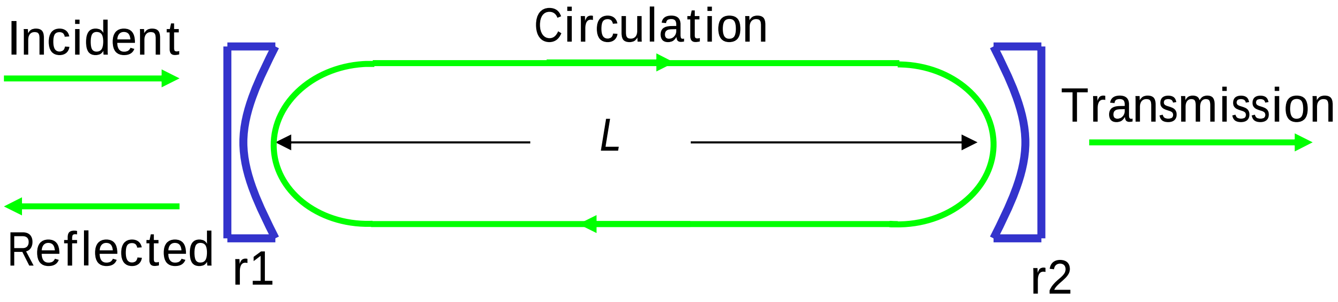
**Green Fabry-Pérot Cavity :** Twice the Analyzing power of present IR cavity, two-fold increase in Figure-of-Merit

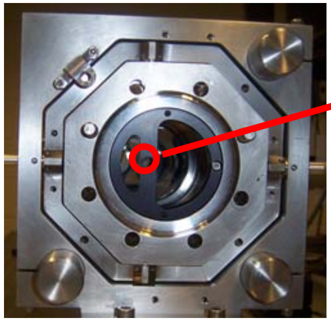
**Dynamic Range :** **2 GeV ~ 6 GeV → 0.8 GeV ~ 11 GeV**

# Green Fabry-Pérot Cavity




| | |
|---|---|
| Wavelength | 532 nm |
| Power | 1,500 Watts |
| Gain | 15,000 |
| Q-factor | $1.8 \times 10^{11}$ |
| Length | 0.85 m |
| Mode | CW, $TEM_{00}$ |
| Free Spectral Range | 176 MHz |
| Cavity Band Width | 3.12 kHz |
| Mirror Reflectivity | 99.996266 % |
| CIP spot size ($\sigma$) | 87 $\mu$m |

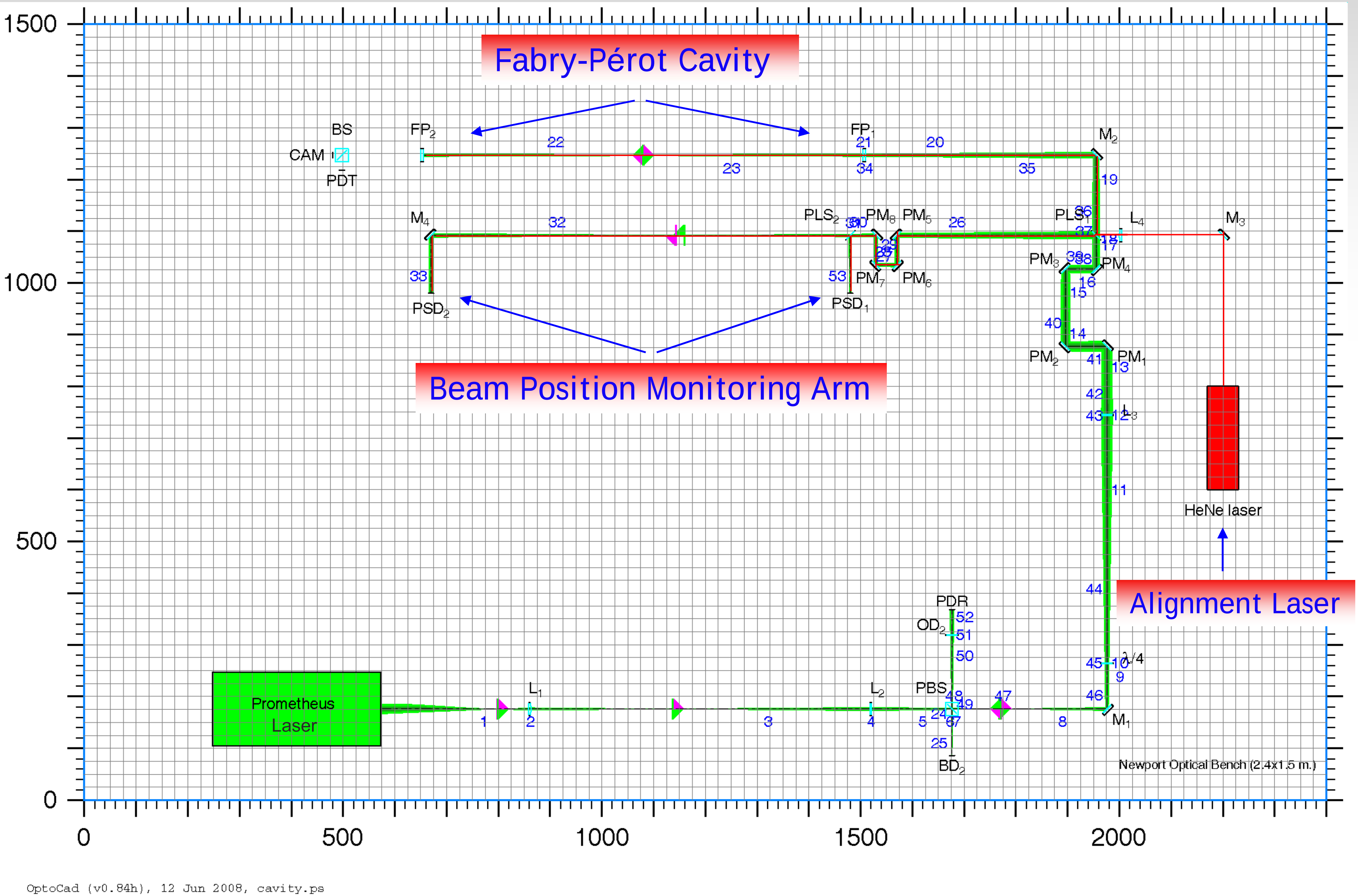


Mounting slot for a cavity mirror

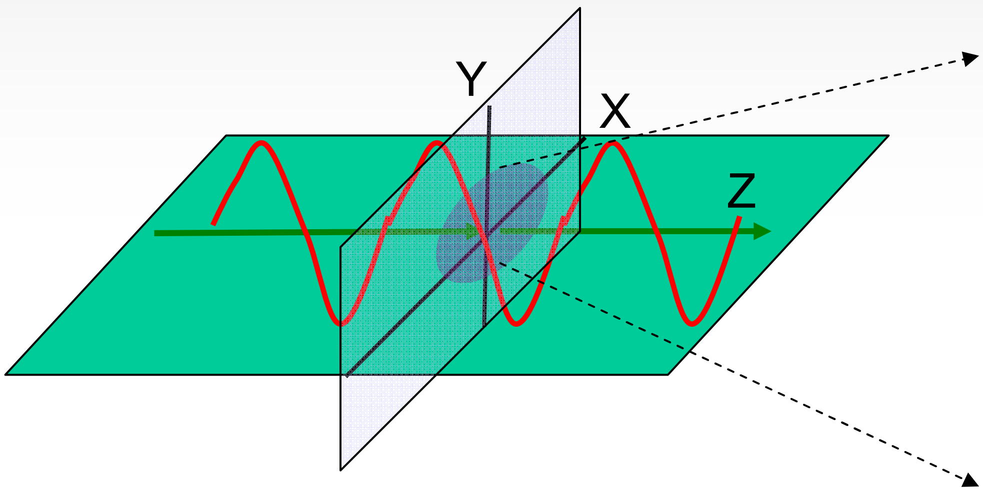
Low power Green Laser -> High Finesse cavity -> Feedback to laser PZT to lock

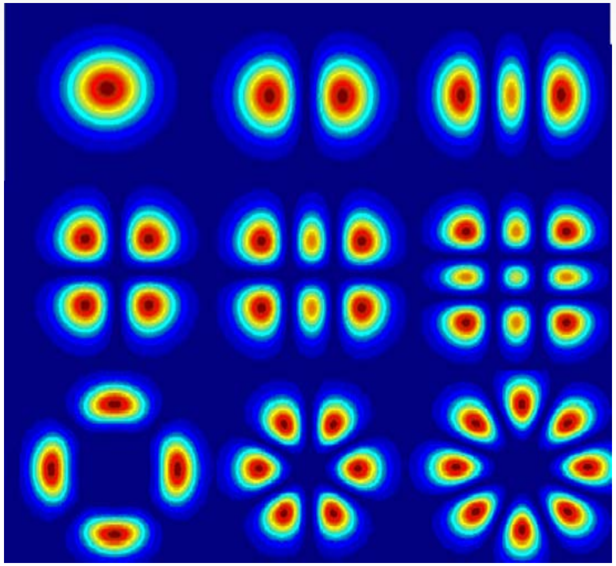
# Optical Setup

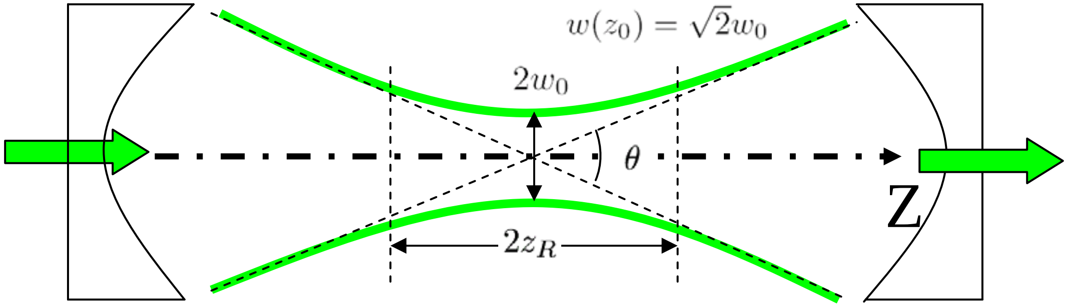


# Cavity transverse mode

$$E(x,y,z)_{mn} = A\frac{d_0}{d(z)}e^{-ikz}e^{i\omega t}e^{i(m+n+1)\Psi(z)}e^{-ik\frac{x^2+y^2}{2R^2(z)}}e^{-\frac{x^2+y^2}{d^2(z)}}H_m\left(\sqrt{2}\frac{x}{d(z)}\right)H_n\left(\sqrt{2}\frac{y}{d(z)}\right)$$



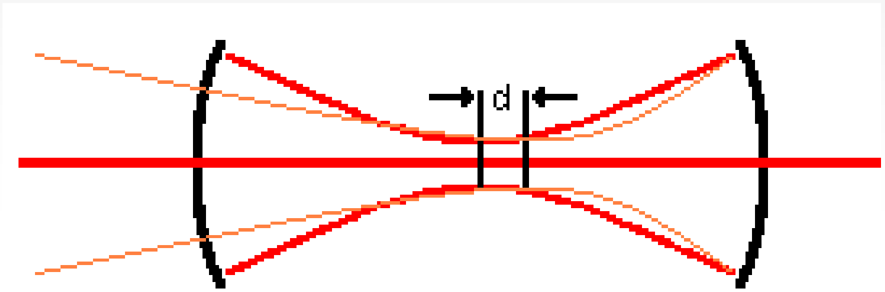


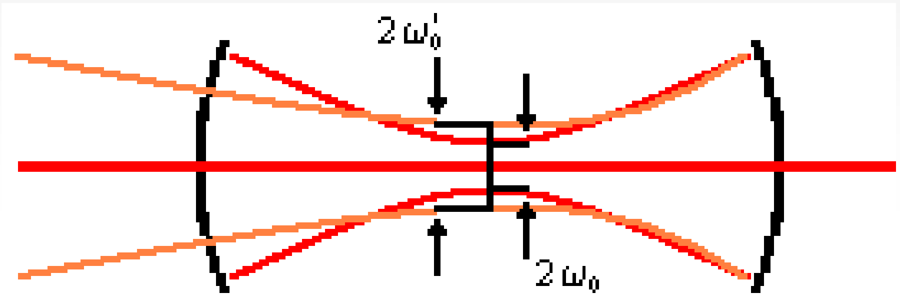

$$w_0^2 = \frac{L\lambda}{\pi}\sqrt{\frac{1+g}{4(1-g)}}$$

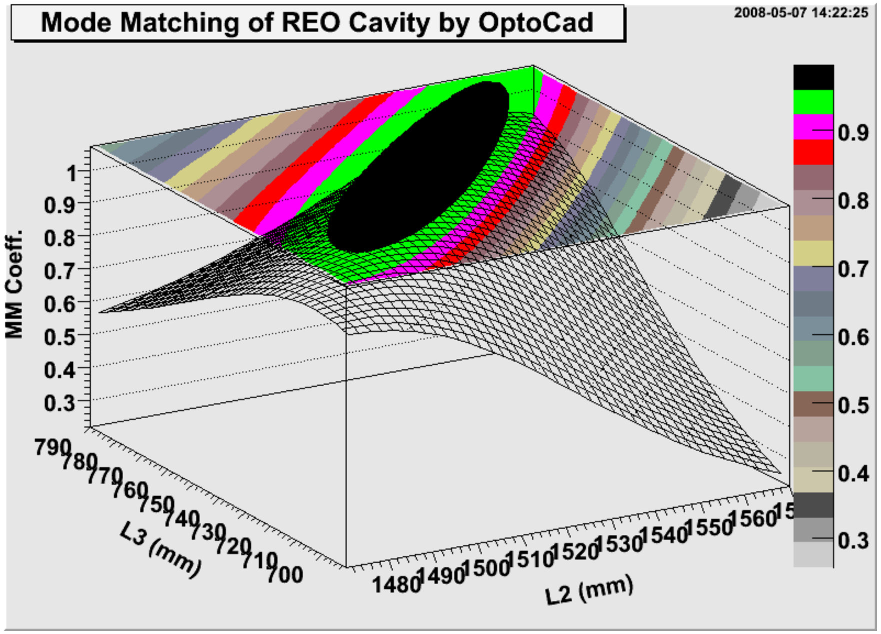
$$g = 1 - \frac{L}{R}$$

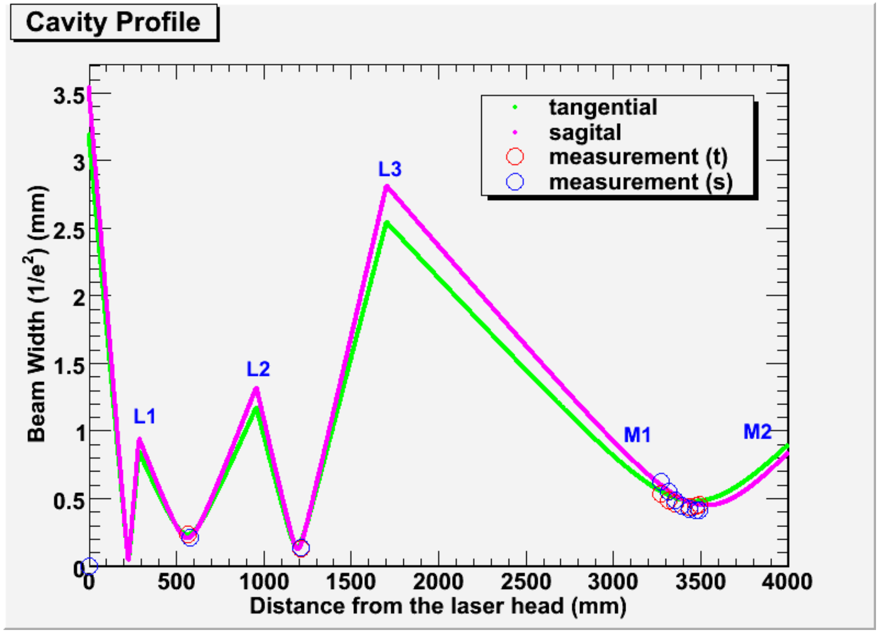
# Cavity Mode Matching

- Laser mode (beam) should match the cavity resonator mode
- Beam waist at the center should match the natural waist of the cavity
- The amount of primary power actually amplified in the fundamental mode



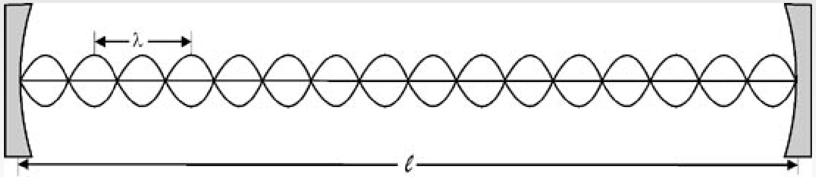



# Cavity Resonance

- Keep the cavity resonate forever
- It is very hard to stabilize the cavity length in **nm** level

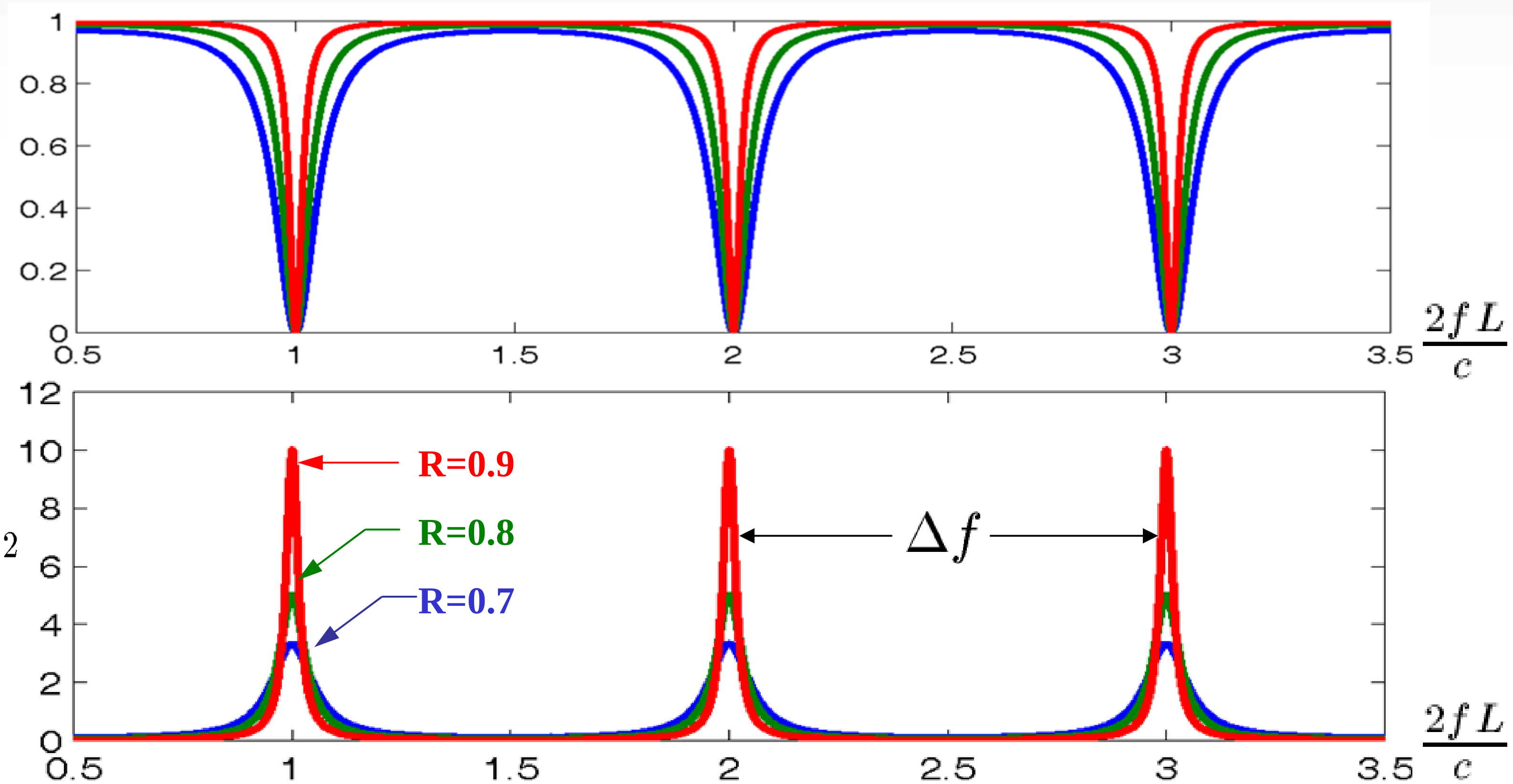
$$L = q\frac{\lambda}{2}$$

$$\Delta f = \frac{c}{2L}$$

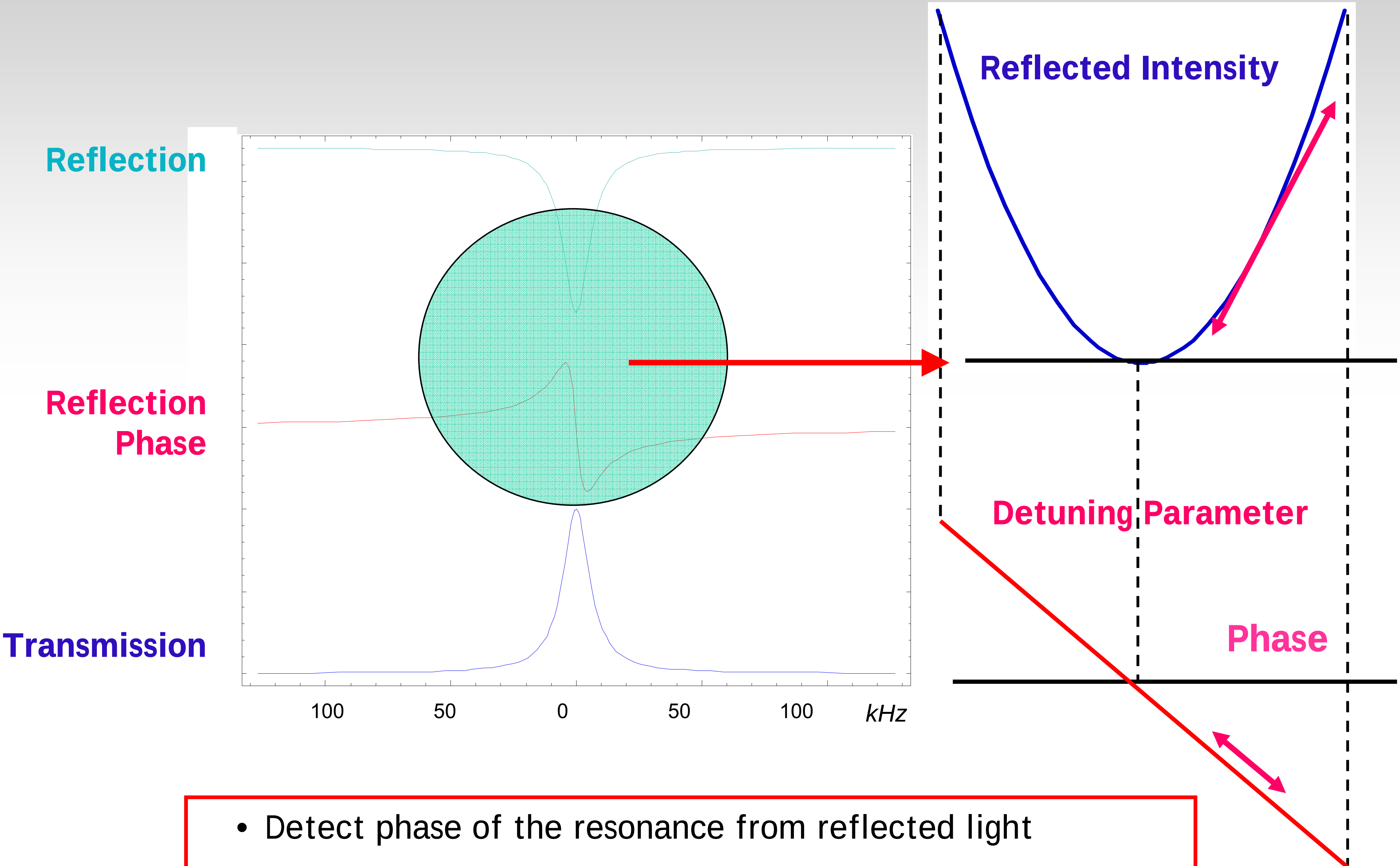



R=$|\frac{E_{refl}}{E_{inc}}|^2$

$Gain = |\frac{E_{circ}}{E_{inc}}|^2$



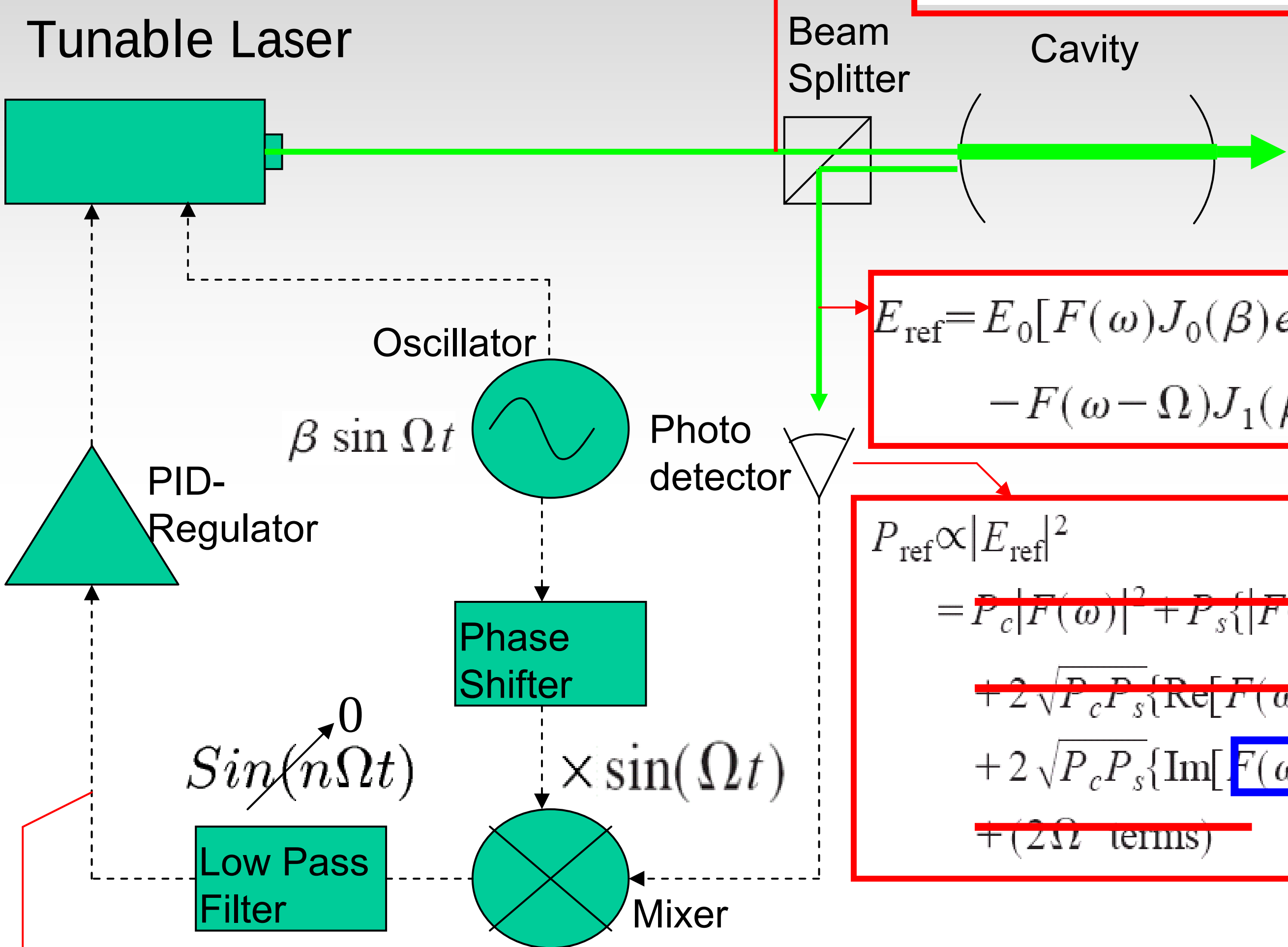
# Characteristic Signals of a Fabry-Pérot Cavity




- Detect phase of the resonance from reflected light
- Feedback to tunable element to stay “locked” to resonance

# Pound-Drever-Hall Locking Scheme

$$
\begin{aligned}
E_{\mathrm{inc}} &= E_0 e^{i(\omega t + \beta \sin \Omega t)} \\
&\approx E_0[J_0(\beta) + 2iJ_1(\beta)\sin \Omega t]e^{i\omega t} \\
&= E_0[J_0(\beta)e^{i\omega t} + J_1(\beta)e^{i(\omega+\Omega)t} - J_1(\beta)e^{i(\omega-\Omega)t}]
\end{aligned}
$$




$$
\begin{aligned}
E_{\mathrm{ref}} = E_0[&F(\omega)J_0(\beta)e^{i\omega t} + F(\omega+\Omega)J_1(\beta)e^{i(\omega+\Omega)t} \\
&- F(\omega-\Omega)J_1(\beta)e^{i(\omega-\Omega)t}].
\end{aligned}
\qquad F(\omega) = E_{\mathrm{ref}}/E_{\mathrm{inc}}
$$

$$
\begin{aligned}
P_{\mathrm{ref}} &\propto |E_{\mathrm{ref}}|^2 \\
&= \cancel{P_c|F(\omega)|^2 + P_s\{|F(\omega+\Omega)|^2 + |F(\omega-\Omega)|^2\}} \\
&\quad \cancel{+ 2\sqrt{P_cP_s}\{\mathrm{Re}[F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)]\cos \Omega t\}} \\
&\quad + 2\sqrt{P_cP_s}\{\mathrm{Im}[\boxed{F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)}]\cancel{\sin \Omega t}\} \\
&\quad \cancel{+ (2\Omega \text{ terms})}
\end{aligned}
$$

$$P_c = J_0^2(\beta)P_0 \qquad P_s = J_1^2(\beta)P_0$$

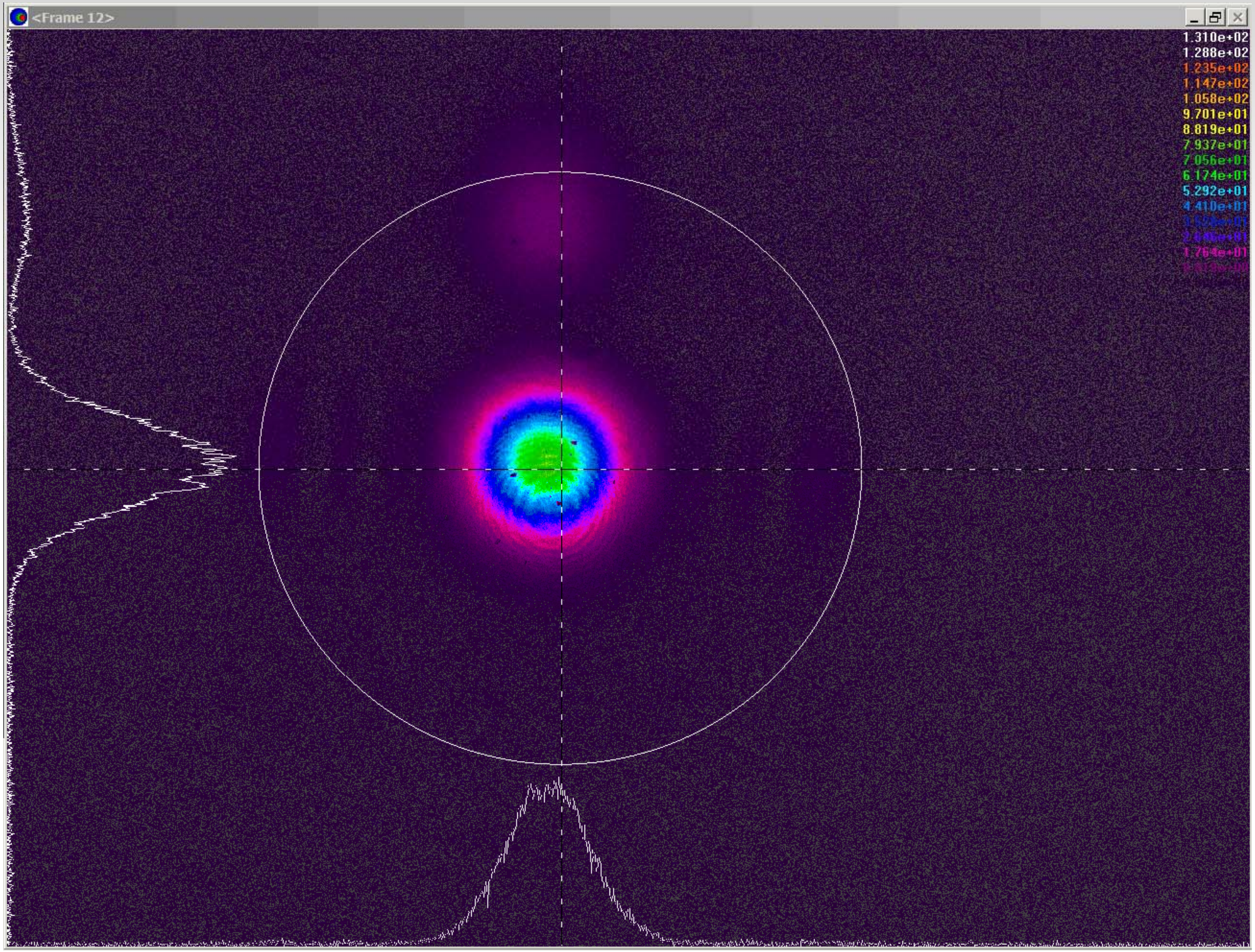
near resonance

$$\Delta\omega_{FSR}/Finesse \ll \Omega \ll \Delta\omega_{FSR}$$

$$F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega) \approx -i2\,\mathrm{Im}\{F(\omega)\}$$

$$\epsilon = -2\sqrt{P_cP_s}\,\mathrm{Im}\{F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)\}$$

# Cavity Locking



# Summary

- Low gain (G ~ 1,000) cavity locking has been accomplished
- Working on design goal cavity (G ~ 15,000) locking

# Compton Lab   ARC L312